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Flood Resilience, Amenity and Biodiversity Benefits of an Historic Urban Pond

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Summary

The main pond within the historic Royal Botanic Garden Edinburgh (RBGE) is an important component of urban Blue-Green Infrastructure. This paper reports on flood resilience provided by the pond (simulated using the CityCAT hydrodynamic model), its water residence times (obtained using the Shetran hydrological model), and the ecology and biodiversity (vascular plants, bryophytes, aquatic invertebrates, phyto- and zooplankton, birds) of the pond and the adjacent area. The results show that the pond improves the flood resilience with at least a 27% reduction in the peak discharge during a one hour, one in 100 year event. The area represents a biodiversity hot spot with a range of native taxa occurring among introduced plant species. The plankton community is dominated by diatoms, reflecting elevated levels of turbulence and a relatively short residence time, with an average value of 10 days. Analysis of macroinvertebrate community indicates a potential for water quality improvement. The results are discussed in relation to multiple societal benefits related to flood resilience, recreation, education, water quality, amenity and biodiversity value. The conclusions may prove particularly valuable for introducing practical measures in the water catchment preventing waterlogging of the soil and ensuring an uninterrupted supply of public services.

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1 Introduction

Blue-Green Infrastructure (BGI) is an interconnected network of natural, semi-natural and man-made landscape features such as water bodies and green spaces, which provide multiple societal benefit functions including water storage, flood risk alleviation, and water purification [1-3]. A network of properly functioning BGI components is an important prerequisite for Water Sensitive Urban Design (WSUD), which focuses on achieving the harmony between people, water, and the natural and built environment, by integrating water cycle management into planning and design [4-5]. Specifically, WSUD aims to protect and enhance natural systems within urban environments; manage water resources and maintain groundwater levels and surface water flows; promote and deliver water conservation; initiate surface water management into developments; and protect public health by providing liveable, resilient and adaptable urban developments [6]. It should be noted that although simulation modelling has been used within the WSUD approach for flooding mitigation and the assessment of peak flows, a recent review [7] revealed that the overwhelming majority of studies focus on event simulations, and there is a need for application of continuous simulations. This research gap may be addressed by case studies combining applications of hydrological models (such as Shetran) and hydrodynamic models (such as CityCAT).

Sustainable Drainage Systems (SuDS) generally refers to the management of surface water runoff only and is an important part of WSUD. The more recent concept of Sponge Cities appears to be the most encompassing. It aims to combine the benefits of other concepts and puts emphasis on the protection and remediation of natural environment, prioritising its ecosystem service function [8 – 10]. Both WSUD and BGI concepts emphasise the value in the connection and interaction of blue and green components, encouraging networks of interconnected BGI assets that can manage, treat and convey runoff and potential flood waters, while also maximising the development of wider benefits [5,11]. Recent work has shown that provision of these multiple benefits is often interlinked, and it is therefore important to consider them in concert [5,12]. For example, through integrating BGI into the wider urban environment, it is possible not only to alleviate the flood risk, increase flood resilience and improve water quality of runoff, but also to improve habitat and connect with wildlife corridors through urban landscapes [5,13,14].

The pond within the Royal Botanic Garden Edinburgh (RBGE) is located in the Inverleith district of Edinburgh, Scotland. It is an important historic component of BGI, having been present for at least 150 years. It is a valuable public educational facility and being near a residential area, it provides an obvious amenity and recreation value for the local community. The pond is highly valued by both the garden's visitors and the local residents [15]. It has a regulatory function for the runoff and provides further multiple benefits related to water quality and biodiversity value. The pond discharges to the Water of Leith (a nearby river) which has a history of flooding issues, causing flooding in Edinburgh in both 2002 and 2012 [16].

Characterisation of the pond's hydrology and biological community is important for the understanding of its overall functioning and provision of ecosystem services [17]. Application of mathematical modelling to characterise the pond's catchment and its hydrological dynamics is particularly useful in that respect, as it helps to account for the complex multivariate interplay between precipitation patterns and the catchment's morphology, soil properties, and vegetation characteristics. Hydrological modelling [18] is particularly useful in understanding the long-term water balance within the catchment and so residence times of water within the pond, whilst hydrodynamic modelling [19] is particularly useful for considering the occasional high intensity, short duration precipitation events and the overland flow within the garden and in the pond.

The aims of this paper are to analyse the multiple benefits associated with flood resilience, recreation, education, water quality, amenity and biodiversity that this historic pond provides. This is achieved by a thorough analysis of the pond's ecology and also the results of detailed physically based hydrological and hydrodynamic modelling. This is extremely relevant as BGI is being added in a lot of cities within the UK [20,21] and worldwide [3,22,23] and it is important to understand the long-term benefits of these features on the hydrology and ecology by considering the effect of an historic well-managed urban pond. This can help overcome uncertainty regarding their hydrological performance and lack of confidence concerning their public acceptability [24].

2 RBGE Pond, Data and Models

2.1 RBGE Pond

The RBGE pond is located within the Inverleith part of the city of Edinburgh, Scotland (Figure 1). The garden moved to its present site in 1820 and it covers 0.28 km^2. The pond was excavated at some point before 1870 and it has surface area of 1,300 m^2 [25] with a volume of approximately 800 m^3 (Figure 2). The volume was measured as part of this work by selecting 80 evenly spaced locations across the pond and taking depth measurements at each location.

The pond is mainly rainwater and groundwater fed, with no permanent inflow, although surface water inflow over the waterlogged soil occurs during major events. The outflow pipe connects the pond to the Water of Leith which then flows north-east out to the Firth of Forth estuary at Leith. It should be noted that for the major part of the garden opening hours the water from the pond is almost continuously pumped up the slope to supply a small ornamental water feature in the rock garden, whence it flows freely back to the pond. This recirculation leads to elevated levels of turbulence and also helps to keep the water oxygenated. High levels of turbulence are known to lead to high resuspension rates, and help to maintain small particulates in the water column, which has an effect on water quality and biogeochemical cycling [26,27].

The catchment area draining into the pond is 0.14 km^2 and this catchment is entirely located within the ground of the RBGE (Figure 3). Within this catchment there is a small valley that starts in the west and heads north-east towards the pond with small hills to the north and south. The hills have till superficial deposits whereas the superficial deposits in the valley are sand and gravel from raised marine deposits; there is a sedimentary base rock of the Gullane Formation throughout the catchment [28]. Freely drained brown soils are predominant in the pond's catchment [29]. Land-use is predominately deciduous parkland with a wide variety of different trees. Two metre resolution LIDAR data of the catchment are available, and daily rainfall data are supplied by a Scottish Environmental Protection Agency (SEPA) rain gauge located within the garden.

2.2 Rain Garden

After heavy or frequent rainfall some areas of the RBGE, including those adjacent to the main pond, become waterlogged and there are a number of problematic spots prone to flooding. As a solution to this problem, a raingarden is being installed by RBGE in partnership with Heriot-Watt University [30]. This SuDS feature is situated on Birch Lawn, in an area which has been set aside for growing native Scottish plants. The raingarden represents a shallow basin that allows natural infiltration through free-draining soil. The site already has a number of both native and introduced trees and full details can be seen in Section 4.4

2.3 Hydrodynamic Model

Hydrodynamic modelling of the RBGE pond catchment was carried out using the CityCAT model [19]. This is a 2D overland flow routing model that enables rapid assessment of combined pluvial and fluvial flood risk. The simulation of the free surface flow is based on the full 2D shallow water equations [31,32] which are able to accurately capture propagation of flood waves as well as wetting and drying of the domain. Hence the model is able to capture the dynamics of the surface water flow towards the pond and within the pond and is therefore suitable for extreme events. It is not suitable for the long-term water balance within the catchment as the model does not simulate subsurface flows or evapotranspiration processes.

The simulation of the RBGE pond uses the 2m LIDAR catchment data with buildings from the OS-MasterMap™ datasets excluded from the grid (but rainfall incident on them drains to adjoining squares). Green areas are also obtained from the OS-MasterMap™ datasets and these areas allow infiltration. CityCAT is used in this work to simulate one in 100 year rainfall events of durations from 15 minute to six hours under the present day ground surface elevations (with and without the rain garden) and also with the ground surface elevation from before the pond was excavated (estimated by assuming a constant slope from the inlet of the pond to the outlet). The raingarden was incorporated into the CityCAT model by reducing the elevation within a 30m by 15m area by 0.5m (NB: the exact dimensions of raingarden are still being finalized).

2.4 Hydrological Model

Characterisation of the pond's hydrology is important for the understanding of its overall functioning and provision of ecosystem services. One measure of this is the pond's nominal residence time [33]. The nominal residence time for each month is calculated as the pond volume divided by the total simulated monthly discharge, converted to days.

Hydrological modelling of the RBGE pond catchment was carried out using the Shetran model. Shetran (http://research.ncl.ac.uk/shetran/) is a physically based distributed modelling system for water flow, sediment and solute transport in river catchments [18,34]. As Shetran includes all the major hydrological processes, including evapotranspiration and subsurface flows it is suitable for simulating the long-term flows into and out from the pond and hence the monthly residence times of the pond. This provides indispensable background information for further analysis of ecological patterns and assessment of overall ecosystem functioning.

The surface water component within Shetran is simulated with the diffusive wave approximation of the full 2D shallow water equations (rather than the full hydrodynamic solution in CityCAT) so the model is unable to capture the full dynamics of surface water flow. It is therefore not suitable for accurately simulating extreme rainfall events, which need to accurately capture the propagation of flood waves in the pond.

Shetran uses a 4m grid resolution of the catchment based on the 2m LIDAR data. This gives 125 by 116 vertical columns with 20 cells in each column containing the soil and geology information (there is a limit of 200 by 200 vertical columns). Simulations were run for 19 months from 1 January 2018 to 31 July 2019 using daily SEPA rainfall measured within the RBGE. These dates correspond to the period of the observations as part of the ecological studies. Average monthly potential evaporation is used, with the data obtained from the CHESS dataset [35]. Based on the measurements, parameters values for the soils, geology and land use were obtained from standard libraries [36].

3 Modelling Results

3.1 Hydrodynamic Modelling Results

The effect of the pond on discharges from RBGE catchment for one in 100 year rainfall events with durations from 15 minutes to 6 hours can be seen in Table 1. It can be seen that the largest flows are for the one hour event (1.65 m^3/s with no pond and 1.20 m^3/s with the pond) so the pond has a significant effect, reducing the peak flow discharge by 27%. The peak flow also occurs five minutes later with the pond present. The pond has the greatest absolute difference in flows for the 30 minute event with a 0.49 m^3/s difference. The greatest percentage difference is for the 15 minute event where the pond produces a 33% reduction in peak flow. For the longer rainfall events there is an increase in the lag with having the pond present, so that for the six hour event the peak flow occurs eight minutes later.

The one hour, one in 100 year event can be considered in more detail by analysing the maximum water depths (Figure 3a). The pond can be clearly seen at the eastern edge of the catchment, where the water depths are greater than 0.4m. Also visible is the valley that starts at the western edge of the catchment and heads north-east towards the pond. Here the water accumulates from the higher elevations on both sides, producing significant surface water depths. The hydrographs for the one hour, one in 100 year event with and without the pond can be seen in Figure 4. The pond reduces the velocities and so reduces the peak flows and increases the lag between the rainfall and the peak flow, although the total volume of water is the same in both cases. This is because the pond has not been designed as a SuDS detention pond and so it is full at the start of this event. It should also be noted that the reduced discharge value of 27% is rather a conservative estimate, as currently the model assumes that the excess water overspills without a considerable restriction and delay. In reality, however, during the recent high rainfall (August 2019) it was observed that the water level rose due to the restriction of the outlet channel, thus further delaying and alleviating the peak discharge. Potentially, these characteristics may be enhanced by altering the shape of the outflow.

Another method to understand the effect of the rainfall events on the RBGE catchment is to consider the resilience and system performance, which varies from 0 (total loss of performance) to 1 (no loss). This work uses the measure suggested by Wang et al. [37] where each grid square is defined as flooded or unflooded. System performance is defined as the ratio of the number of unflooded grid cells to the total number of grid cells and flood resilience is the aggregation of system performance over the entire simulation. In this case the depth threshold which categorizes a cell as flood or unflooded is set to 20mm. Figure 5 shows the lowest system performance occurs for the 30 minute event with a value of 0.81 (i.e. 81% of the catchment has a flood depth less than 20mm). As expected, the longer events have a higher system performance but the reduction in performance lasts for a longer period of time.

3.2 Hydrodynamic Modelling Results with a Rain Garden

The effect of the rain garden on the pond outflow for one in 100 year rainfall events for durations from 15 minutes to 6 hours can be seen in Table 1. For the one hour event this reduces the peak flow to 1.07m^3/s a further reduction of 11%. There are similar reductions for the other duration events. The effect of the rain garden on maximum water depths in the catchment for the one hour, one in 100 year event can be seen in Figure 3b. The rain garden fills up and so the simulated water depths within the rain garden are greater than the original simulation without the rain garden. This stored water reduces the maximum simulated water depths along the temporary waterway towards the pond by about 20 mm and the water depths in the pond by around 50mm. In particular for this 100 year event there is some reduction in flooding along the path. It can be seen in Figure 4 that in this case the rain garden is acting as a SuDS detention feature as there is a reduction in the total flow leaving the pond, with this volume corresponding to the amount stored in the rain garden (which was empty at the start of the simulation). Whereas the pond, which is full at the start of the simulation and has a much larger volume (800 m^3 compared to 225m^3 for the rain garden), is just reducing the velocities and so the total volume leaving the pond is the same as with no pond present.

The effect of the rain garden results in a small increase in system performance. For the 30 minute event the effect is at its maximum 5 minutes after the peak precipitation with 1.8% (450m^2) of the previously flooded area no longer classed as flooded.

3.3 Hydrological Modelling Results

Modelling of the RBGE catchment using Shetran was carried out for a 19 month period (Figure 6). The mass balance for 2018 shows that precipitation was 571mm (compared to the 1860-2005 long term average for central Edinburgh of 686mm [38]), with a potential evapotranspiration of 449mm. The model simulated a discharge of 214mm with an actual evapotranspiration of 420mm. This gives a reduction in subsurface water storage of 63mm which is as expected for a drier than average year. Figure 6 shows a wet spring period in 2018 with high discharges and a dry summer in the same year with low discharges. Discharges in 2019 show less variability.

The pond's nominal residence time (pond volume divided by the monthly water inputs) calculated every month using Shetran can be seen in Table 2. The average residence time is 10.0 days but it varies from 4.7 days during a wet April 2018 with 66 mm of precipitation to 146.4 days in July 2018 which was generally warm and sunny with only 32 mm of precipitation. The highest discharge was simulated as a result of 48mm of rainfall in three days from 2/4/2018 – 4/4/2018 with a nominal residence time of three days during this period. It is acknowledged that these nominal residence times are limited in explaining the actual residence times within the pond. A more complete description is described by the residence time distribution, which describes how likely it is a water molecule will stay in the pond for a given duration. This is useful as it indicates both dead zones, which have a longer residence time, and short-circuiting, which causes a significant part of the flow to exit the pond much earlier [33,39,40]. In the RBGE pond there is significant growth of vegetation in the summer, reducing mixing, which will significantly affect the short-circuiting and dead zones [41].

It should be noted that the annual mass balance totals are realistic and it has been possible to confirm that the simulated base flow is approximately correct by making use of engineering work that was carried out on the pond during a period of low rainfall. Over 48 hours on the 8-9/11/2018 about 90% of the water was drained from the pond in order to install a new pump part. This reduction in volume was achieved by opening the sluice gate which, once the part had been successfully added, was then closed and the pond allowed to naturally refill. By 19/11/2018 the pond's water volume was substantially replenished, although it was still lower than normal by approximately 0.2m. Using information from the pond depths this suggests 475m^3 of water entered the pond during this 10 day period with just 7mm of precipitation. The Shetran inflow to the pond during this period corresponds very well with a total of 456m^3

Examples of simulated water table depths for the entire catchment on 10/3/2018 and 18/7/2018 are given in Figure 7. The pond can be seen on the eastern edge of modelled area with the water table depth above ground. Heading south west along a valley from the pond the water table is close to the ground surface whereas higher up to the north and south of the modelled area the water table is much deeper. The water table depth on 10/3/2018 is much closer to the ground surface than on 18/7/2008. On 10/3/2018 there was 50 mm of rain in the previous 10 days, whereas on 18/7/2018 there was 1mm of rain in the previous 10 days and evapotranspiration rates were also much higher during this summer period. This again gives confidence that the model is simulating realistic flows as saturation excess overland flows are simulated during periods of heavy rainfall such as around 10/3/2018.

It should also be noted that some aspects of the pond's dynamics are by default not represented by the Shetran simulations. For example, it was observed that the outflow got blocked on 9 February 2019, and a week later that water level rose by about 0.3m, which resulted in flooding and subsequent closure of a viewing platform and an adjacent path.

4 Ecological Studies Results

In addition to the flood resilience benefits described above, the RBGE pond provides a number of further ecosystem services. These include multiple benefits related to recreation, amenity and biodiversity values, as well as trapping of pollutants. This section gives an overview of the results obtained through ecological studies in order to characterise these benefits. Water quality was assessed by regular sweep net sampling of aquatic invertebrates.

4.1 Sweep Net Sampling

Sweep net samples of macroinvertebrates were taken bimonthly from two sampling points. The ASPT index was calculated on the basis of macroinvertebrate data and this shows that the majority of the samples were characterised by ASPT values of 2.4-3.9. This is lower than expected values reported elsewhere [42], and the water quality appears to be unsuitable for some sensitive taxa (e.g. damselflies). However, these values are somewhat higher than the previous measurements in 2015 – 2016 when the median values of 2.2 and 2.6 were reported for the sampling points close to the outflow and inflow respectively [43], although the maximum value of 6 reported previously greatly exceeds the values so far observed in our research. Interestingly, following the maintenance event in November 2018, the ASPT values dropped only slightly (to 2.4 and 3 for the points close to inflow and outflow respectively).

Among invertebrate taxa regularly encountered in the samples were *Corixidae*, *Asellidae*, *Chironomidae*, *Lymnaeidae and Oligochaetae*. Most of the animals found in the samples are tolerant of poor water quality conditions. For example, the frequently encountered representatives of *Mollusca, Crustacea* and *Hemiptera* were, respectively, *Radix baltica, Asellus aquaticus* and *Sigara dorsalis,* which are all tolerant of a wide range of environmental conditions. *Coleoptera* were found in the samples only infrequently and contained representatives of *Haliplidae* (*Haliplus sibiricus* and *H. flavicollis*), *Elmidae* (*Elmis aenea*) and *Helophoridae*

(*Helophorus aequalis* and *H. brevipalpis*). Water mites, an Ephemeropteran *Cloeon dipterum* and leeches *Glossiphonia complanata* and *Herpobdella octoculata* were also recorded.

Although there is clearly a potential to enhance the water quality and the diversity of macroinvertebrate community, it is currently sufficient to support a population of three-spined stickleback *Gasterosteus aculeatus*, which has been frequently observed in the sweep net samples.

4.2 Plankton

Between 6 and 35 planktonic taxa were registered on specific sampling occasions. The samples from May, August and October 2018 and April-May 2019 all rendered 24 or more planktonic taxa. The highest species richness was recorded in October 2018.

The phytoplankton community in the RBGE pond appears to be dominated by diatoms. Large filaments of cf. *Diatoma* and *Melosira* were frequent in the samples, and *Fragillaria* was also encountered. Pennate diatoms were also variably registered in good variety, with *Synedra* being present in all the samples. Such a prominence of diatoms in RBGE is likely to be caused by higher turbulence resulting from a combination of a relatively low residence time (estimated using the Shetran model) and artificial recirculation. The water from the main pond is pumped to a small water feature in the rock garden, whence it flows downhill back to the main pond; this regular circulation results in elevated levels of turbulence.

In addition to diatoms, dinoflagellates (*Gymnodinium* and *Peridinium*) were also encountered in a number of samples. In particular *Gymnodinium* persisted through three consecutive months, being frequent in July – September 2018. Cyanobacteria (mainly *Oscillatoria*) were present throughout the warmer season, but were never encountered in elevated quantities. The low numbers of cyanobacteria may be related to the combination of a relatively low water residence time and elevated turbulence. Representatives of *Chlorophyta* (Figure 8) were always present in the samples but in rather variable quantities and with no consistent occurrence of any particular species. The August 2018 net sample was particularly diverse in respect of *Chlorophyta*, and had elevated numbers of e.g. *Phacus*, *Chlamydomonas*, and filaments of *Mougeotia*. *Cryptomonas*

(*Cryptophyta*) were frequent in October and also present in a number of other samples. *Chrysophyta* were present on several occasions, with *Synura* being frequent in February 2019.

Zooplankton were, generally speaking, seldom abundant. However, Copepods were frequent in June and September. The October sample had a good variety of rotifers and protozoa, although only *Rotaria neptunia* and *Euplotes* were frequent.

It should be noted that in addition to frequently encountered planktonic taxa, the sample variously contained many rarer taxa. Figure 9 gives examples of the noteworthy representatives of testate amoebae (*Arcella* and *Trinema)* and Euglenozoa (*Trachelomonas*)

4.3 Vegetation

Overall, the RBGE pond is characterised by a very high biodiversity value as it has a mix of native and introduced species.

4.3.1 Vascular plants

The plant community around the pond and in the Botanic Garden in general is very diverse and contains a mix of native and introduced species. To date, over 100 species of vascular plants have been reliably observed around the RBGE pond. A number of plants are specifically associated with mesic and aquatic habitats (*Caltha palustris*, *Deschampsia cespitosa*, *Nuphar x spenneriana*, *Phragmites australis*, *Veronica beccabunga, Mentha aquatica, Potamogeton bertholdii*). However, the majority of the plants found around the RBGE pond are terrestrial. These include many planted shrubs (*Rosa* spp., *Spiraea salicifolia, Cornus kousa*, *C. foemina*, *Weigela* sp., *Rhododendron* spp.) and trees (*Acer tataricum*, *Aesculus sylvatica*, *Betula kenaica*, *Crataegus douglasii*, *Magnolia acuminata*, *Salix* spp., *S. x sepulcralis*, *Quercus palustris*, C*ercidiphyllum magnificum*, *Ilex verticillata, Viburnum foetidum, Nyssa sylvatica*). Some planted native shrubs, e.g. *Myrica gale* and *Cytisus scoparius* are also present.

There are also a number of both planted and spontaneously occurring herbaceous plants. The planted herbs may be found both as scattered individual specimens (*Doronicum* sp., *Geranium* spp.) and in flower beds (e.g. *Dianthus* sp., *Ligularia dentata*, *Petasites* spp., *Phlomis fruticosa*, *Polygonatum multiflorum*, *Primula* spp., *Tanacetum vulgare*, *Vicia* sp., *Iris douglasiana, I. versicolor*, *Mimulus* sp., *Hosta lancifolia*, *H. sieboldiana, Lamiastrum* *galeobdolon*, *Helenium autumnale*, *Fragaria virginiana*, *Potentilla recta, P. goldbachii, Vincetoxicum hirundinaria*, *Hemerocallis esculenta*, *Astelia nervosa*, *Aquilegia caerulea*, *Crocosmia pottsii*, *Gunnera manicata*, *Bergenia* sp.), whilst the naturally occurring ones (e.g. *Artemisia vulgaris*, *Barbarea* sp., *Cardamine flexuosa, Chameanerion angustifolium, Digitalis purpurea, Epilobium hirsutum, Filipendula ulmaria*, *Galium aparine*, *Geum rivale, G. urbanum*, *Lamium album*, *Plantago major*, *Ranunculus repens*, *Rubus fruticosus*, *Rumex sanguineus*, *Scrophularia nodosa, Silene dioica, Stachys sylvatica*, *Urtica dioica*) are scattered throughout the area. The same pattern is also evident for grasses. Some notable examples of planted Graminae include ornamental *Miscanthus sinensis*, whilst native species are represented by *Alopecurus pratense*, *Bromopsis ramosa, Deschampsia cespitosa*, and *Festuca rubra*, among others. There are also plantings of ornamental sedges *Carex* spp. (*Carex elata*, *C. pendula*). There are also native planted (*Osmunda regalis*) and naturally occurring ferns (*Dryopteris filix-mas*) and horsetails (*Equisetum arvense*).

Potentially the species list might become much longer, as there are many labels indicating past plantings, but that needs to be corroborated by further observations.

4.3.2 Bryophytes

Twenty-one species of bryophytes have been recorded around the pond in a variety of microhabitats. The majority of bryophytes found were mosses. *Amblystegium serpens*, *Kindbergia praelonga*, *Tortula muralis, Hypnum cupressiforme*, *Brachythecium rutabulum* and *Bryum capillare* have been registered on dry rocks, whilst *Didymodon tophaceus* on wet rocks. *D. insulanus, Syntrichia latifolia* and *Funaria hygrometrica* have been found on stone blocks. A number of moss species were also found on the bark of mature trees (*Orthotrichum affine, O. diaphanum, O. pulchellum, Rhynchostegium confertum, Syntrichia papillosa, Ulota bruchii* and *U. crispa*), whilst *Grimmia pulvinata* revealed both epiphytic and calcicolous affiliation, occurring on trees as well as on dry rocks. *Mnium hornum* and *Plagiomnium undulatum* have been found on soil, the former species around the trees and shrubs, the latter on disturbed ground.

Only two species of liverworts, *Lunularia cruciata* and *Metzgeria furcata*, have been observed around the RBGE pond. Both species were recorded on dry rocks, and no liverwort species have been revealed on planted trees and shrubs. The reason for the lack of epiphytic liverworts is unclear, as many mosses were recorded on tree bark, and should be investigated by further research.

4.4 Rain Garden

Within the rain garden site and its immediate surroundings, there are already a number of both native and introduced trees, including *Corylus sieboldiana* (Japan, Korea), *C. avellana* (native), *Alnus rubra* (N. America), *A. glutinosa* (native, although the specimen on site is listed as a hybrid), *A. japonica* (Japan), *Quercus robur* 'Filicifolia' (cultivar of a native species), *Betula alleghaniensis* (NE North America), *Betula papyrifera* (N North America), *B. nigra* (USA), *B. pendula* (native) and *Populus alba* (S and Central Europe). Some of these trees are particularly well suited for wet conditions (e.g. *Betula alleghaniensis, Alnus* spp., *Populus alba*). In addition, there are plantings of a rather large herbaceous plant *Gunnera manicata* (Brazil), also well suited for the damp conditions. A big specimen of holm oak *Quercus ilex* located just south of the rain garden helps to intercept the subsurface runoff from higher elevation. Further landscaping is planned with a selection of plants tolerant of occasional flooding, and continuous observations of the planted specimens are very valuable in that respect (Table 3). In the future, it is intended to give priority to plant species native to Scotland, thus creating a shift towards a naturally occurring ecological community. This will also enhance biodiversity value of invertebrate animals which co-evolved to use this type of ecosystem as a habitat. Ideally, these plants will also be characterised by relatively high evapotranspiration rate traits.

4.5 Other surveys

Further current and planned ecological surveys include vegetation, fungi, lichens and vertebrate animals. Particularly important for the amenity value provided by the pond are birds, as it attracts many bird watchers. A number of species can be found around the feature, including *Parus major, Cyanistes caeruleus, Gallinula chloropus, Erithacus rubecula, Dendrocopos major, Pica pica, Prunella modularis, Pyrrhula pyrrhula, Sylvia atricapilla, Sitta europaea, Streptopelia decaocto, Anas platyrhynchos* and *Alcedo atthis.* From this list, it is evident that this BGI pond's species richness benefits from the ecotone (interzonal effect), as woodland species (blue and great tits, nuthatch, woodpecker) can be encountered in close proximity to those typical of aquatic habitats (moorhen, mallard, kingfisher). The occurrence of a substantial fish population (see section 4.1) is crucial for the presence of the frequently observed kingfishers *Alcedo atthis*, an iconic species particularly favoured by visiting bird watchers.

5 Discussion and Conclusions

The monitoring and modelling study described in this paper provides important information on the historic and well-maintained RBGE pond, thus aiding interpretation of its overall functioning and provision of multiple benefits associated with ecosystem services. The results of hydrodynamic modelling show that having the pond has caused a 27% reduction in peak discharges for a one hour, one in 100 year rainfall event. It should be noted that the pond's catchment is only a small part of the Water of Leith catchment, so the effect of the pond on flows in this river will be small. However, the RBGE pond is part of a network of a large number of pieces of BGI. This network has the potential of significantly improving flood resilience under extreme rainfall events.

As well as improving the flood resilience the pond has an important amenity and ecological function. Our work has shown that although water quality in this BGI pond appears to be relatively low (based on the macroinvertebrate community sampling), the species richness of various biological groups in and around the pond contributes to an overall high biodiversity value. It is known that Green and Blue-Green Infrastructure help to improve habitat connectivity and provides wildlife corridors through urban landscapes [5,13]. There is strong evidence that the area around the RBGE pond functions well in this respect, as many native vascular plant species have been recorded alongside the planted exotics. Also, despite the acknowledged problems with the water quality, the pond accommodates a number of algae, zooplankton and macroinvertebrate taxa. Furthermore, in the area around the pond the diversity of habitats due to plantings and landscaping, and the availability of microhabitats with elevated and relatively stable humidity, appears to be beneficial for the species richness of native bryophytes. Application of hydrological modelling tools is helpful for understanding the biodiversity of the site and planning further management actions.

It should also be noted that a relatively low water quality is indicative of the fact that the pond is trapping pollutants from the runoff. It is therefore acting as a retention pond, thus providing a safety buffer for the downstream ecosystems of the Water of Leith. Further work should address the issue of potential improvements in water quality [44]. In addition it is acknowledged that there is a scope for further improvement in validation of the hydrological modelling and the estimation of residence times of the pond. Further work is suggested to accurately measure the discharge from the pond outlet and also tracer tests to measure the residence time distribution within the pond. This will enable the link between the residence times and the water quality to be improved.

With ongoing climate change, rainfall in Scotland is set to become more frequent and intense; specifically, climate modelling predicts more intense rainfall together with an overall precipitation increase in winter and decrease in summer [45]. The results of hydrodynamic modelling presented here may prove particularly valuable for introducing practical measures preventing waterlogging of the soil and ensuring uninterrupted supply of public services by the Botanic Garden. A rain garden which is currently being installed by the RBGE in one of the more problematic areas is just one example. There are other areas in the RBGE which may benefit from installation of SuDS, and hydrodynamic simulations would provide useful information for such a choice, as well as other management actions.

The biodiversity of the area around the pond contributes to its high amenity value. The pond is enjoyed by hundreds of visitors every day and is part of a general tour around the garden. For the period between 2011 and 2019, the total yearly numbers of visitors to the RBGE ranged between 679,756 and 929,140. As the pond lies on the intersection of all major routes, it is expected that the majority of visitors (around 80-90%) will also visit the pond. Hence there are at least half a million people benefitting from the pond's amenity value each year, and that is a rather conservative estimate. The pond is valued highly by local residents. A previous study [15] used contingent valuation analysis to estimate the annual value of the pond for the local community at £416,160. Furthermore, the balance between Net Present Value (NPV) benefits and capital and operational costs over 50 years was estimated at £8,983,787. The inference was made that the high perceived monetary value of the RBGE pond was largely owing to its aesthetics, flower beds in the surrounding gardens and the abundance of wildlife. Our study certainly supports that, and provides some further insight.

Artists have been observed obtaining inspiration from the pond's view whilst creating their landscape paintings (Figure 10). Furthermore, it is regularly used by schools, university students, wildlife recorders and natural history groups for observational and educational purposes. According to our observations, the pond is particularly popular with bird watchers. The interzonal effect (ecotone), the variety of plantings, and the occurrence of both native and introduced species in close proximity, all contribute to its high educational and recreational value.

However, the monetary value previously allocated to the pond is likely to have been underestimated. During the festive periods in winter, the pond functions as part of a 'Christmas at the Botanics' light display (Figure 10). The attendance during evening hours is charged, hence the visitors have to pay to see the display. The contribution of the pond's aesthetics to the collected revenue has not yet been estimated. It should also be noted that the NPV of the pond's benefits was previously estimated only on the basis of the willingness to pay for it by local residents, i.e. those living within 500 m distance. In reality, most visitors come from farther away. The grounds (including the pond) are very popular among the population of the city, and the attendance is facilitated by an excellent bus network. Furthermore, many of the visitors are tourists, including those coming to Edinburgh from overseas. The outreach of the pond's benefits is therefore far beyond the immediate locality, and the overall NPV is likely to be much bigger than the previous estimate based on its value for the local residents. Further studies should aim to provide a quantitative estimate for the overall NPV taking into consideration the above discussion.

Our results give an insight into multiple benefits provided by this historic well-managed urban pond. This is important as recently BGI has begun to be considered as a vital addition in many cities within the UK [20,21] and worldwide [3,22,23]. However, public perception of these features can be variable [5], and it is important to understand their long-term benefits on the hydrology, ecology and amenity of the surrounding areas. Our research on the RBGE pond helps to overcome uncertainty regarding the hydrological and ecological performance of BGI and lack of confidence concerning their public acceptability [24]. The RBGE pond provides a good example of multiple benefits associated with BGI and could be used as a 'role model'. The results presented here are, therefore, applicable elsewhere, and will be of use both for further research, and for practitioners and policy makers.

Additional Information

Data Accessibility
Model datasets and results from this work are available in an external repository [46]. A video of the 'Festive Flotilla' which is part of the 'Christmas at the Botanics' lights display is also available in an external repository [47]

Model data and results for simulations of the Royal Botanic Garden Edinburgh:
https://doi.org/10.25405/data.ncl.10255736
Video of the 'Festive Flotilla' which is part of the 'Christmas at the Botanics' lights display:
https://doi.org/10.25405/data.ncl.11342072

Authors' Contributions
VK - led the study design, data collection, field and lab work, analysis and interpretation, write-up/editing, and contributed to the modelling.
SB - led hydrological and hydrodynamic modelling, provided a major contribution to the analysis and interpretation, and write-up/editing, and contributed to the field work and study design.
SA - secured funding and contributed to the study design, as well as editing the manuscript.
DK and DK - led the work on raingarden. David Knott also contributed to editing and supply of photographic materials. RM and KW - contributed to the raingarden section.
Derek Christie - participated in field and lab work, and contributed to the section on plankton, data processing and interpretation.
David Chamberlain - led the bryophyte studies.
PB - contributed to field work, data collection and interpretation, to the write up of the vegetation section, and to the provision of photographic materials.
JB - contributed to lab work, to data interpretation and the write up of the plankton section, and to editing of the manuscript.
HF - contributed to field and lab work, to data interpretation and to editing of the manuscript.
YM - contributed to lab work, to data analysis, and the interpretation of invertebrate results.
All authors read and approved the manuscript.

Competing Interests
The authors declare that they have no competing interests.

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Table 1. Peak discharges and delayed time to peak (compared with no pond) for different storm durations for a one in 100 year event

Storm Duration	Total Rainfall (mm)	Peak Rainfall Rate (mm/hr)	No Pond	With Pond		With Pond and Rain Garden	
			Peak discharge (m^3/s)	Peak discharge (m^3/s)	Delay (minutes)	Peak discharge (m^3/s)	Delay (minutes)
15 minute	24	227	1.17	0.78	6	0.65	9
30 minute	31	182	1.60	1.11	5	0.95	7
1 hour	38	136	1.66	1.21	5	1.07	7
2 hour	46	94	1.44	1.13	6	1.03	7
3 hour	52	74	1.22	0.99	7	0.92	8
6 hour	65	47	0.79	0.68	8	0.64	10

Table 2. RBGE simulated monthly pond nominal residence times

Month	Residence time (days)
Jan-18	5.3
Feb-18	5.4
Mar-18	4.9
Apr-18	4.7
May-18	10.0
Jun-18	22.1
Jul-18	146.4
Aug-18	26.4
Sep-18	19.8
Oct-18	23.7
Nov-18	13.9
Dec-18	8.3
Jan-19	11.3
Feb-19	11.2
Mar-19	7.4
Apr-19	14.8
May-19	22.4
Jun-19	14.5
Jul-19	12.0

Table 3. Conditions of plants in the main raingarden area of the RBGE in Nov 2019.

Accession Number	Specimen	Conditions
20052004*A	*Alnus japonica*	good
20091881*A	*Alnus rubra*	good
20171866*A	*Anthyllis vulneraria*	alive
20160501*A	*Aquilegia formosa*	good
20150167*A	*Aruncus gombalanus*	alive
19551029*A	*Astilbe rivularis*	questionable
20090344*I	*Betula alleghaniensis*	good
20090347*P	*Betula papyrifera*	good
19952553*H	*Betula pendula* ssp. *szechuanica*	good
19991851*C	*Cicerbita alpina*	alive
19831043*A	*Corylus sieboldiana*	fair
20171861*A	*Festuca altissima*	fair
20171863*A	*Filipendula ulmaria*	alive
19599789*H	*Gunnera manicata*	alive
19694776*E	*Hosta sieboldiana*	alive
19734130*A	*Hosta sieboldiana*	alive
19694882*D	*Iris pseudacorus*	alive
20171865*A	*Knautia arvensis*	alive
19370182*A	*Ligularia dentata*	good
20061350*C	*Ligularia fischeri*	alive
19698201*C	*Populus alba*	fair
20161117*A	*Primula poissonii*	alive
19698320*A	*Quercus robur* 'Filicifolia'	excellent
19950983*B	*Rodgersia pinnata*	alive

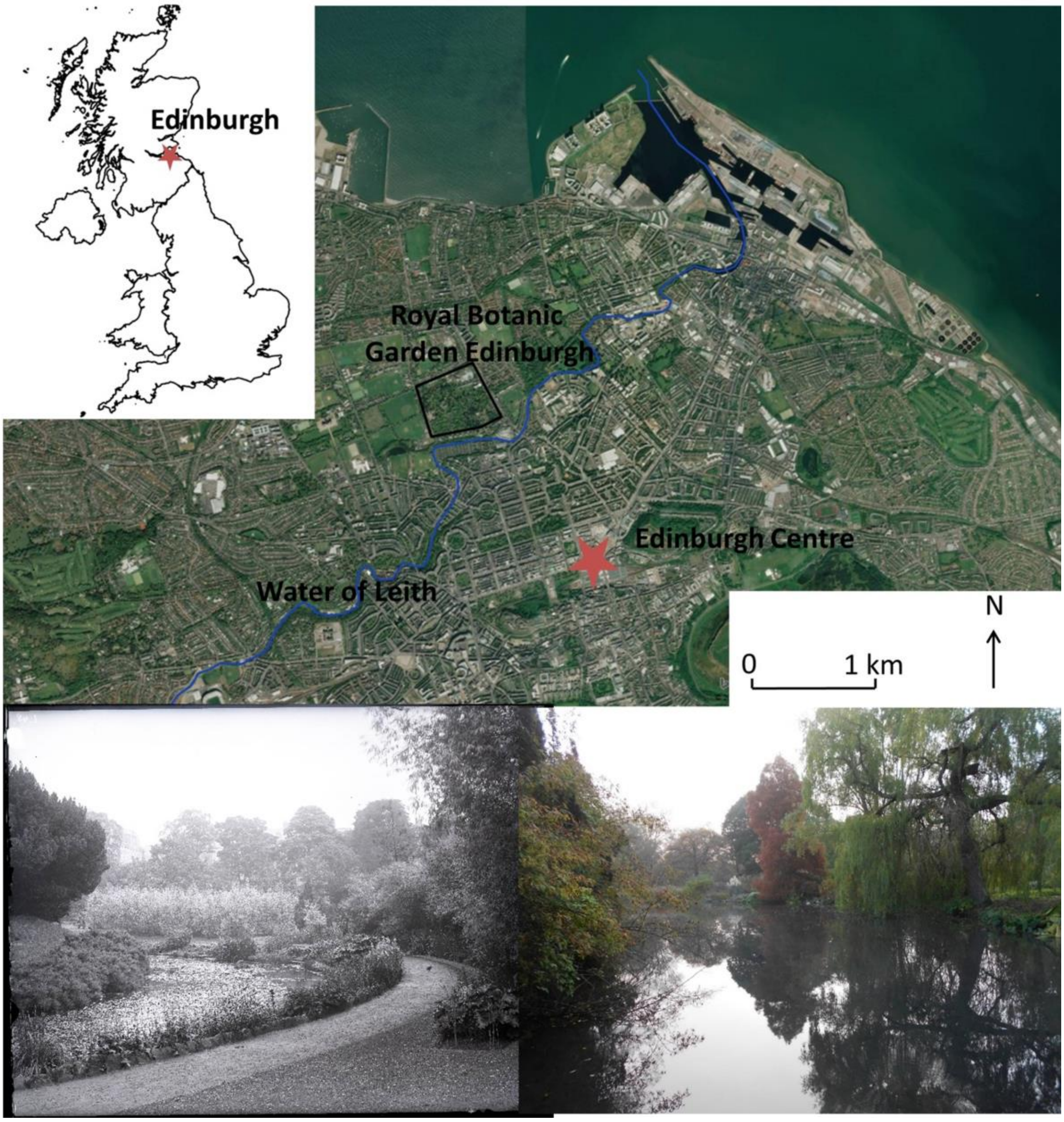

Figure 1. The location (upper panel) and views of the RBGE pond. Lower left – beginning of the 20th century; lower right – current.

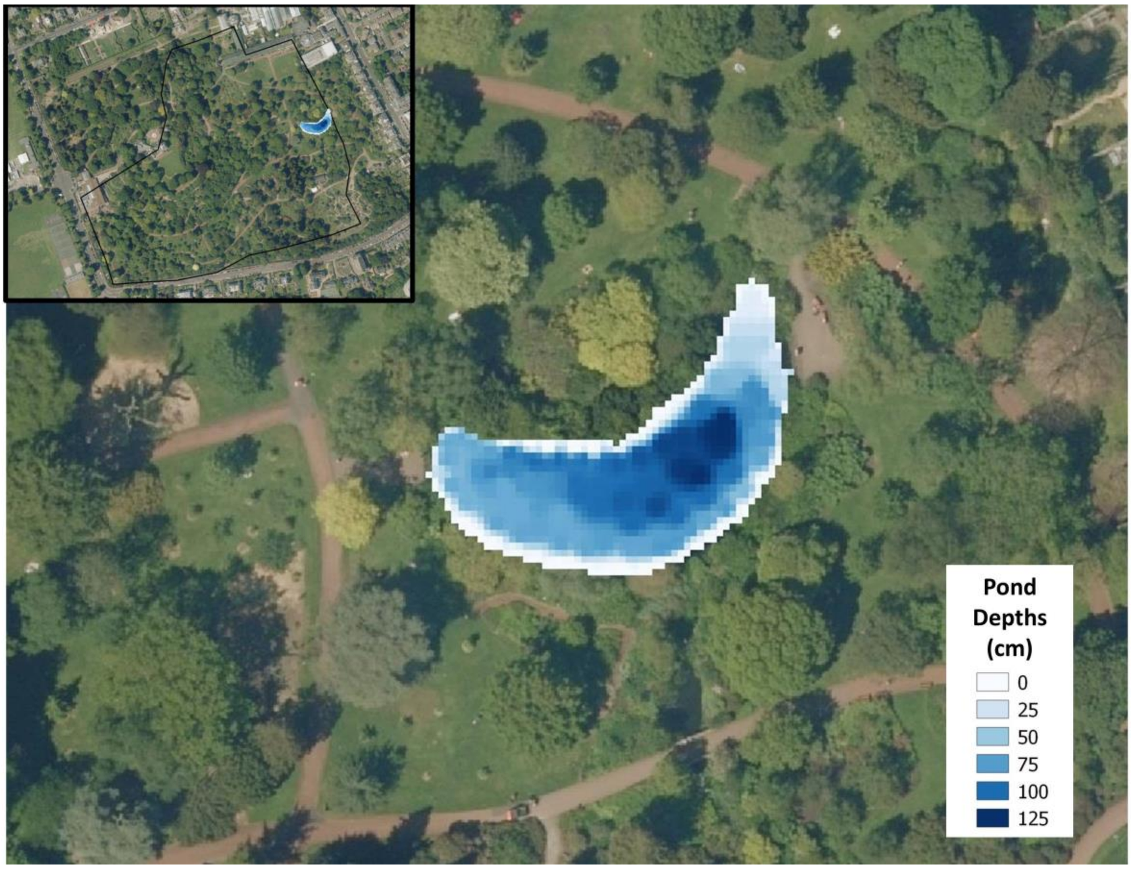

Figure 2. RBGE pond's depth. The insert shows the catchment boundary for water that drains into the pond together with the pond's depths.

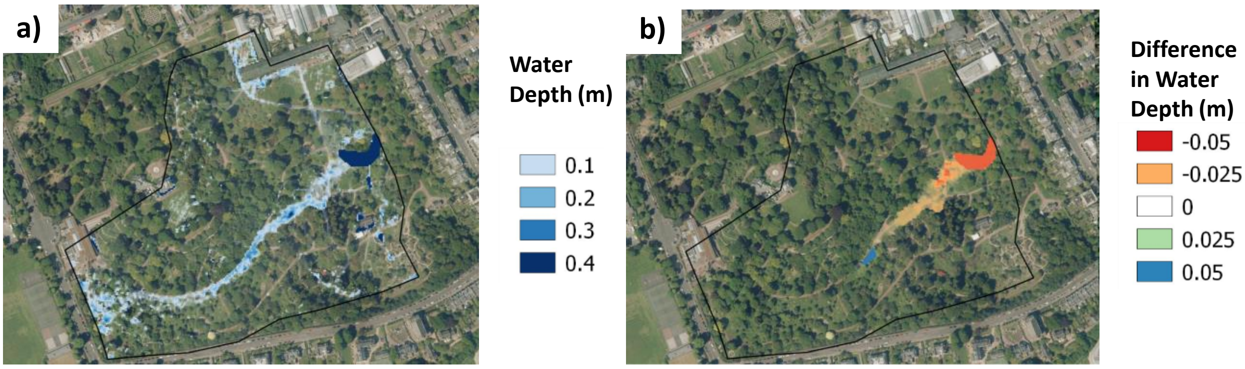

Figure 3. CityCAT model of a one hour, one in 100 year rainfall event simulated with a 2m DEM. a) showing the maximum water depths during the event. b) showing the difference in water depths with the rain garden incorporated into the model. The black line shows the catchment boundary for water that drains into the pond which has an area of 0.14 km^2.

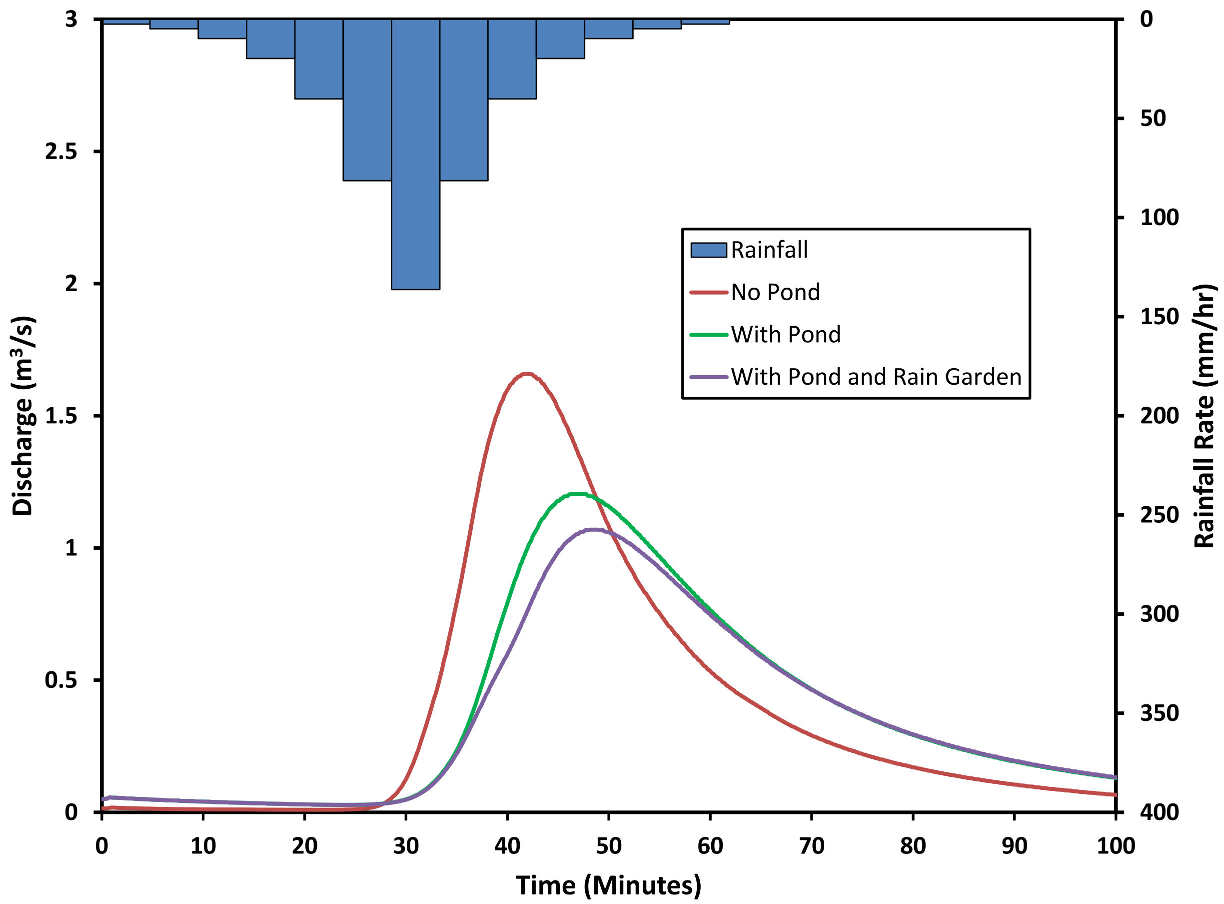

Figure 4. CityCAT simulated discharges for a one hour, one in 100 year rainfall event for the current pond with and without the rain garden and also with no pond (corresponds to the original condition).

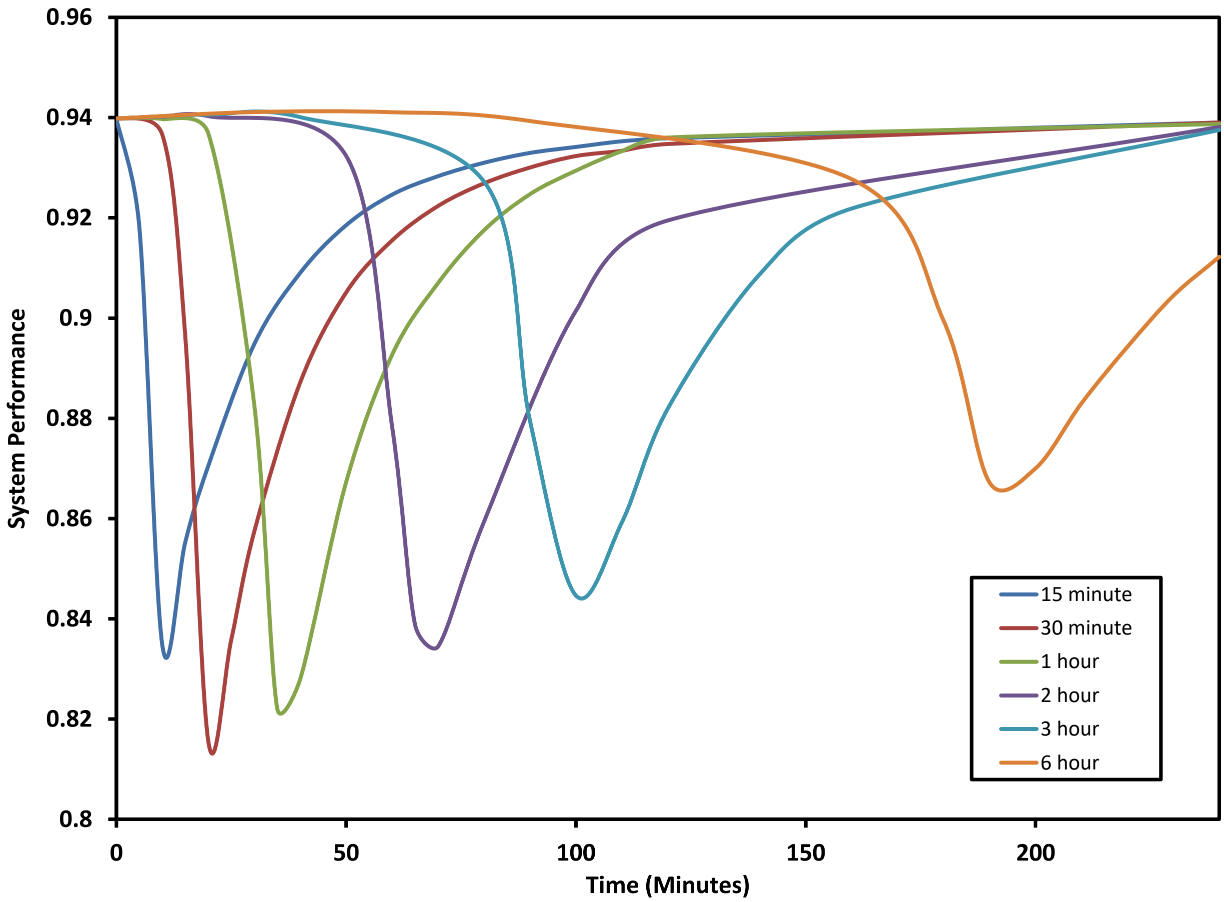

Figure 5. CityCAT simulated system performance for a one in 100 year rainfall event of different durations for the current pond. System performance is defined as the ratio of the number of unflooded grid cells to the total number of grid cells.

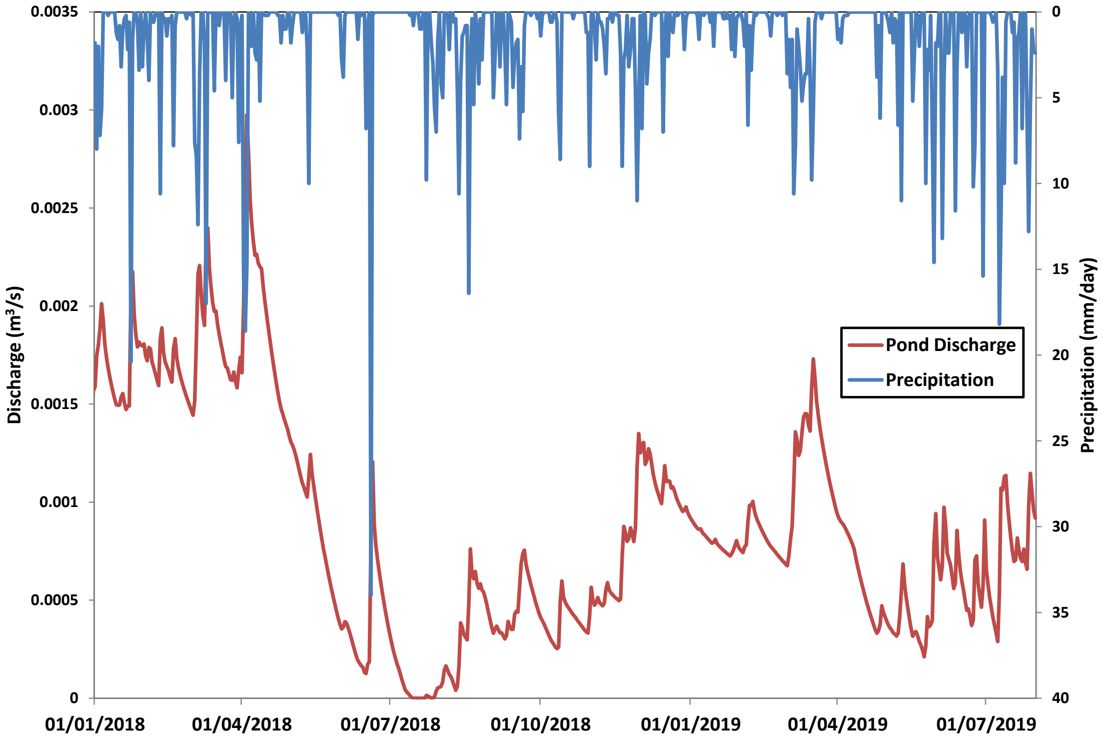

Figure 6. Results of Shetran modelling: discharge rate of the RBGE pond outflow and measured precipitation

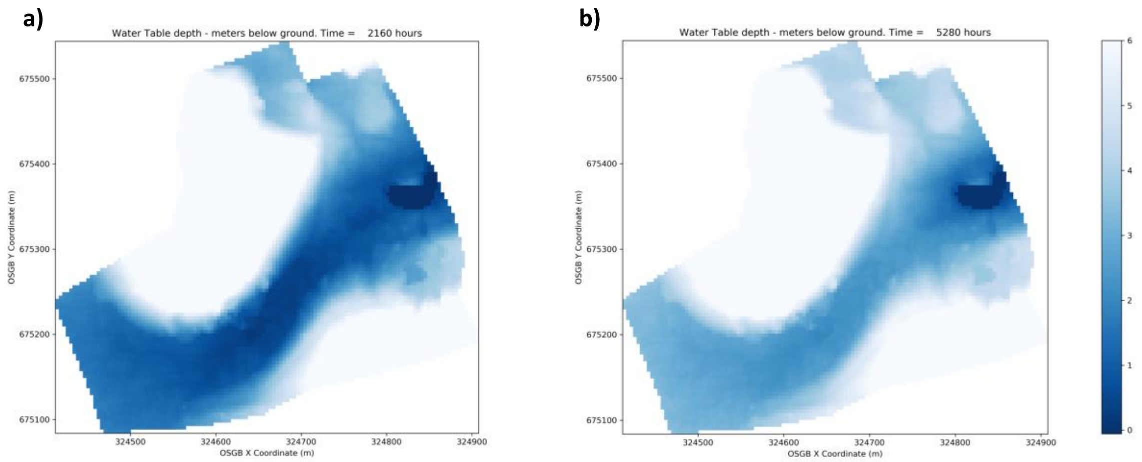

Figure 7. Shetran simulated water table depths (m below ground) for the RBGE catchment. a) 10/3/2018 and b) 18/7/2018

Figure 8. Example of regularly encountered filamentous algae from RBGE pond. Left: Chlorophyta (*Mougeotia* sp); Right: Bacillariophyta (cf. *Diatoma* sp).

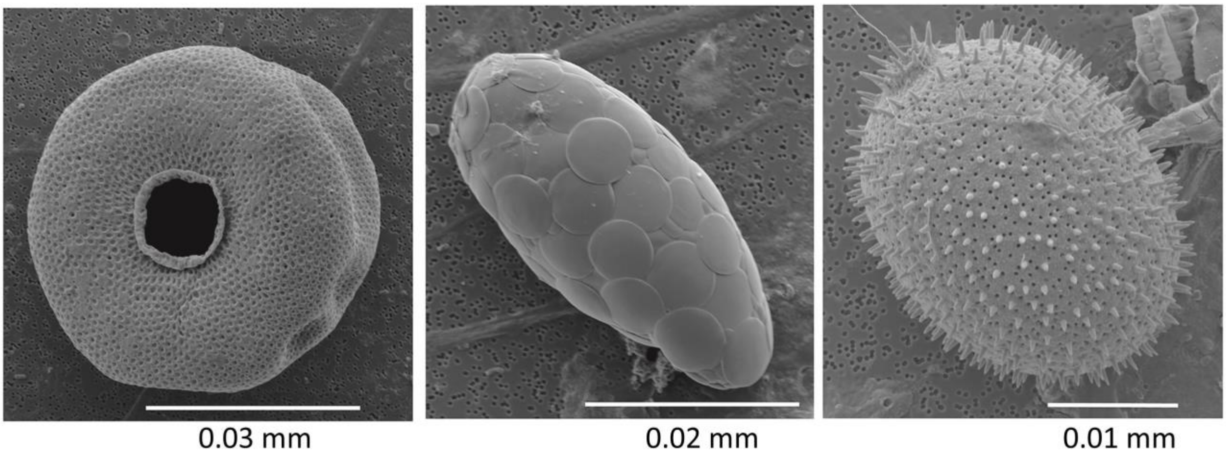

Figure 9. Examples of rarely encountered organisms from RBGE pond. Left: *Arcella* (Amoebozoa); Middle: *Trinema (*Cercozoa*)*; Right: *Trachelomonas* (Euglenozoa).

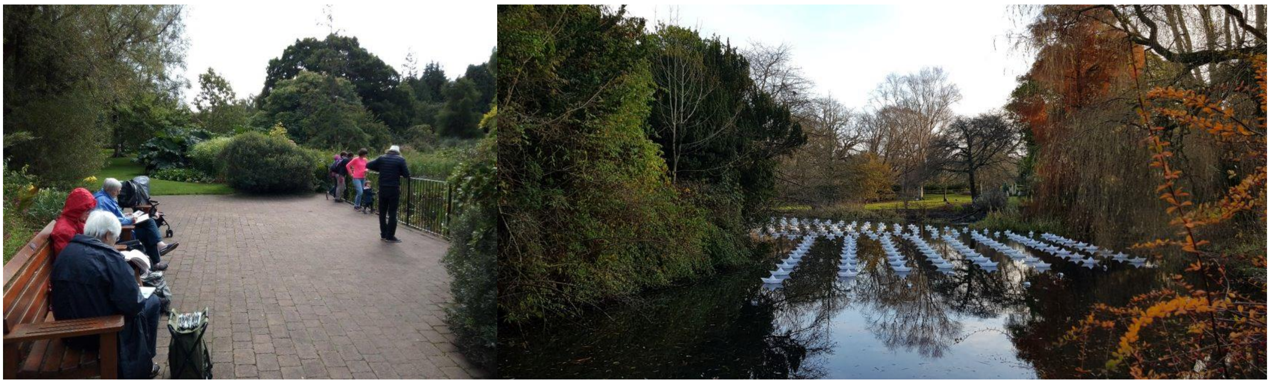

Figure 10. Evidence of high amenity value at the RBGE pond. Left: general public and a local artists' group enjoy making use of the RBGE pondscape. Right: a view of the pond in preparation for the 'Festive Flotilla' which is part of the 'Christmas at the Botanics' lights display.